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USE OF RADAR NETWORK DATA FOR FORECASTING RAIN

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1. Introduction

In this paper we discuss the use of data from a network of radars for weather forecasting, in particular forecasting rain. We illustrate the impact of the data in a practical context, and discuss the cause and nature of quantitative errors in the forecasts based on radars. The results that we present are due either to Collier and Larke (1981), who have described an objective forecasting procedure, or to Browning et al (1981), who have discussed the use of a weather radar network for forecasting rain.[1,2]

Browning has recently reasserted the potential of radar for qualitative or semi-quantitative observations of rainfall over very large areas.[3] A network of only 12 radars would provide complete coverage for the British Isles (Taylor and Browning).[4] With this potential in mind, the UK Meteorological Office has established a Pilot Project to investigate the use of radar for forecasting, in particular the forecasting of rain, in the British Isles. Our experience to date and the results that we present in this paper are based on a network of four radars covering the western half of England and Wales (figure 1).

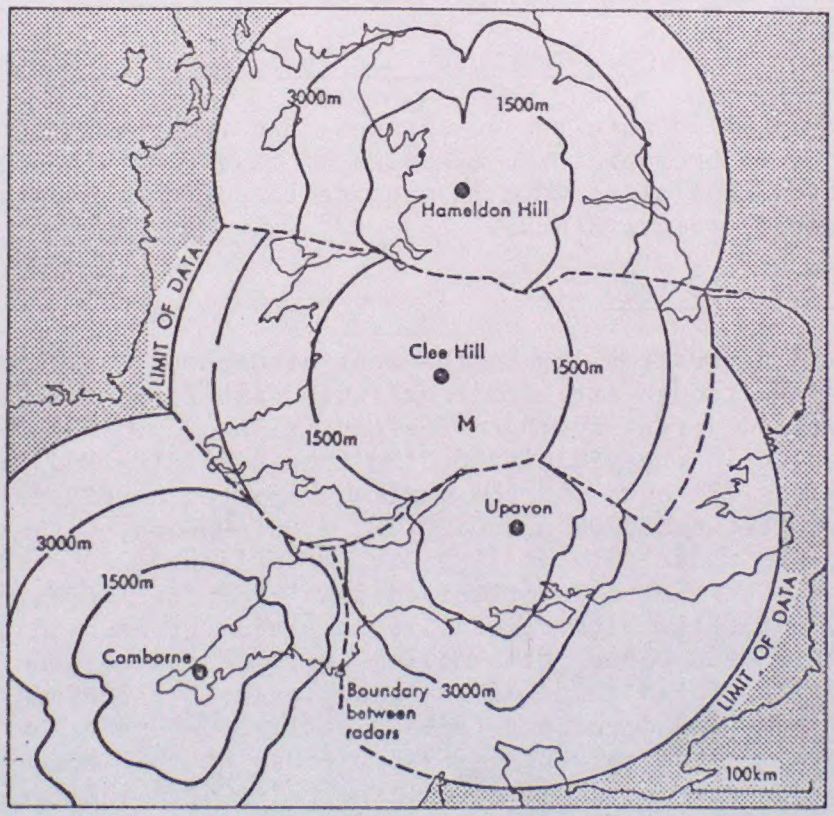

Figure 1. Coverage of the UK weather radar network at present. The outer frame minus the shaded areas shows the total area of the radar composite map derived in real time. The height of the lowest beam for each radar is represented by the 1500 and 3000 m contours. The dashed lines are the boundaries between the radars used in deriving the composite map. The letter M south of the Clee Hill radar shows the location of Malvern, which is referred to in the text.

The Dee Weather Radar Project showed that radar can provide quantitative measurements (± 20%) of rainfall for river subcatchments.[5] It also showed that this ability is limited to ranges of 50 to 75 km, whereas radar will detect rain at much greater distances. Many factors limit the accuracy with which one can infer surface rainfall from these radar observations (eg Collier).[6] We shall argue that these factors are the greatest source of errors in the rainfall forecasts based on radar but that, even so, their impact is small in relation to the potential contribution of a radar network to a weather service. We shall show that, in spite of the miscellaneous errors that are evident to the meteorologist, a simple objective forecast model can achieve an accuracy that would be useful for most customers.

Browning emphasised the importance of assessing radar observations of rainfall in the context of the general meteorological situation, but the reverse relationship is just as strong.[3] In a forecasting environment, radar will be one tool among many and the role of any data source, or computer forecast product, will depend on the particular event. In Section 2, we present three cases in which an operational radar network would have been particularly useful.

Collier and Larke's work on the automatic, objective forecasting of rain is presented in Section 3. In Section 4 we examine the sources of error in these objective forecasts with a view to finding the best way to improve our use of radar in the future.

2. The Meteorological Impact of Radar Data

To illustrate the advantages that radar brings to the weather forecaster we present three examples of cases where conventional synoptic observations alone were inadequate to define the extent and development of mesoscale rain systems.

(i) 29 July 1980

A depression lay to the west of Cornwall and at 1200 GMT an associated thundery trough extended from south east Eire along the south coast of Wales and across southern England (figure 2). Thunderstorms had been reported in the vicinity of the trough in Eire and Cornwall during the previous 12 hours but the maximum reported hourly rainfall was no more than 6.2 mm between 0700 and 0800 GMT at St Mawgan, Cornwall.

The radar data at 1200 GMT, as presented on a TV display (figure 3) shows the rain to be organised in a group of narrow bands with several embedded cells with rainfall intensities greater than 16 mm hr^{-1}. The radar showed these cells moving north west along the bands, while new rainbands developed ahead of the group and old rainbands decayed to the rear. One such band developed rapidly at 1200 GMT near the mouth of the river Severn. Although surface observations at this time gave no indication of this significant development, the radar data indicated that cells of very heavy rain would continually traverse the mountainous and well populated south eastern corner of Wales.

In the next two hours, more than 30 mm of rain fell causing flash flooding in several rivers in South Wales (figure 4).

(ii) 5 June 1980

An active but slow moving cold front lay north south along the Irish Sea at 0900 with very warm and humid air over England and Wales. Careful analysis of the low level wind flow indicated a line of convergence about 100 km to the east of the analysed cold front and this proved to be the preferred area for storm development. Forecasts were for showers in the

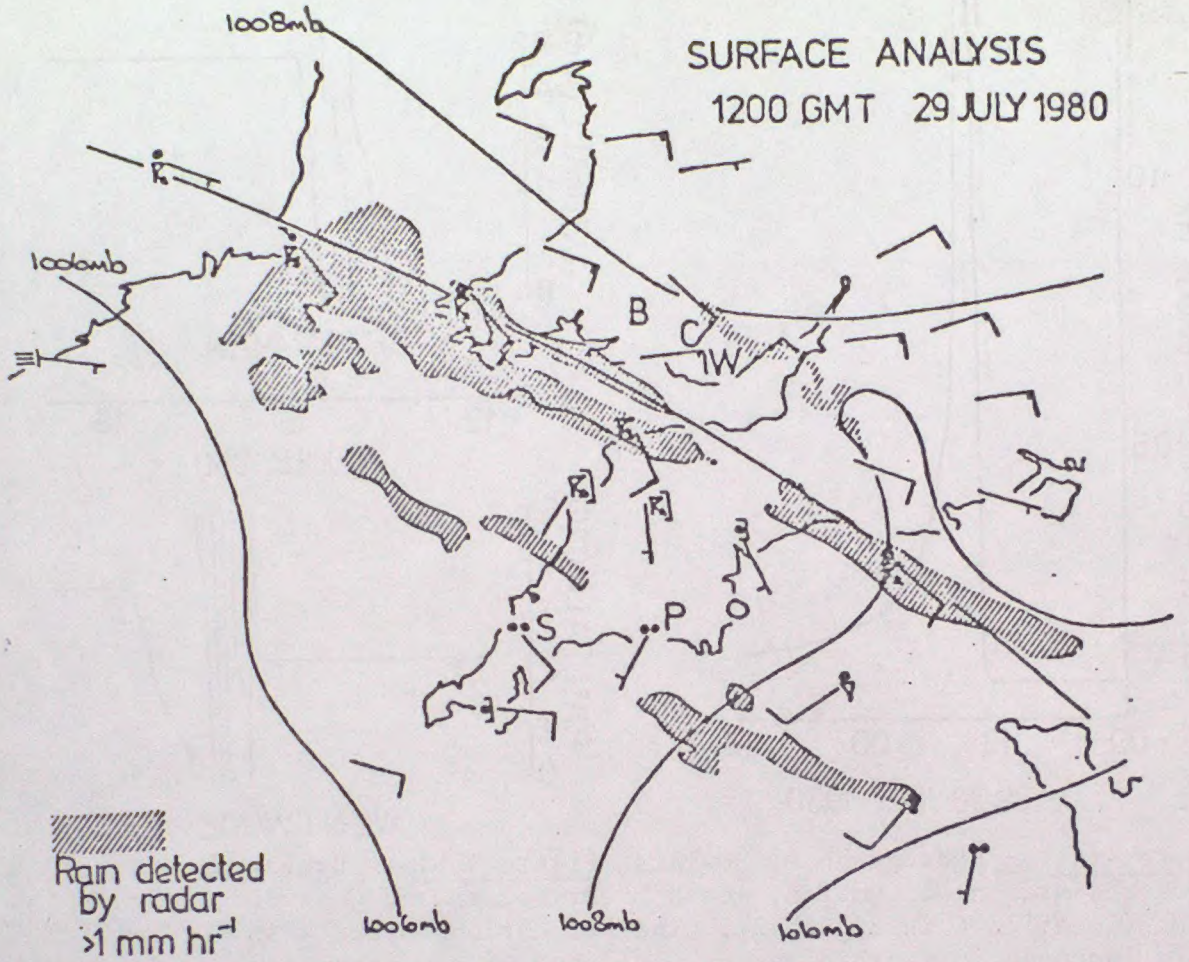

Figure 2. Synoptic chart for 1200 GMT 29 July 1980 showing the analysed position of a thundery trough. Note how surface observations fail to resolve the true extent of the rain (shown shaded) as indicated by corresponding radar data.

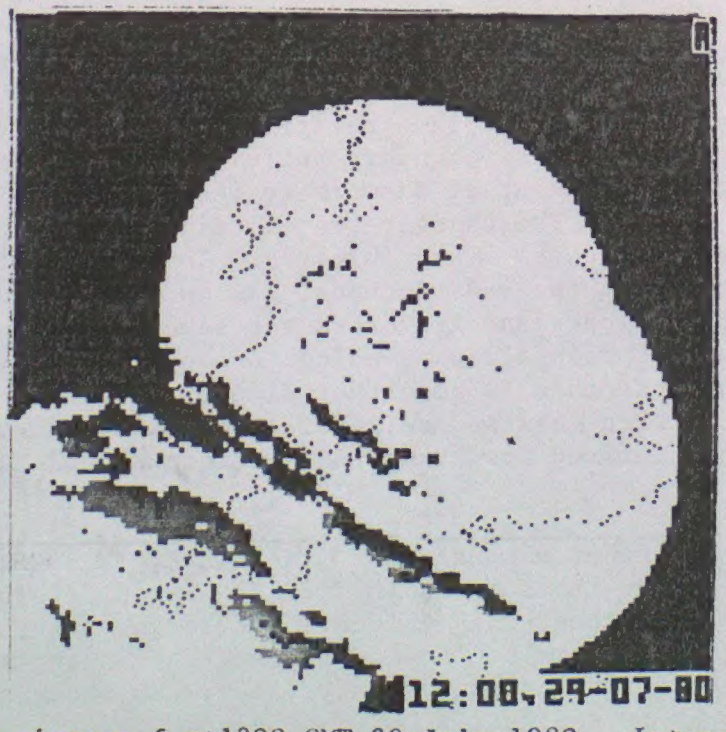

Figure 3. Radar picture for 1200 GMT 29 July 1980. Intensity colour scheme: dark grey 0-2 mm hr^{-1}, light grey 2-8 mm hr^{-1}, white > 8 mm hr^{-1}. The short rainband over the mouth of the River Severn is rapidly developing at this

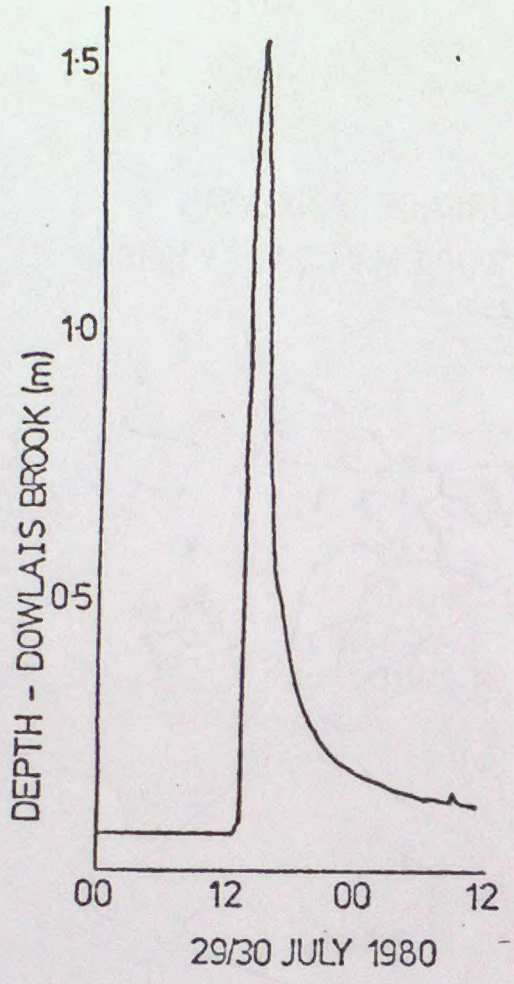

Figure 4(a). Hydrograph of Dowlais Brook measured near Cwmbran, south Wales (location C in figure 2). The rapid increase in depth of some 1.5 m in less than 2 hours is due to run off from the mountainous area affected by a developing rainband.

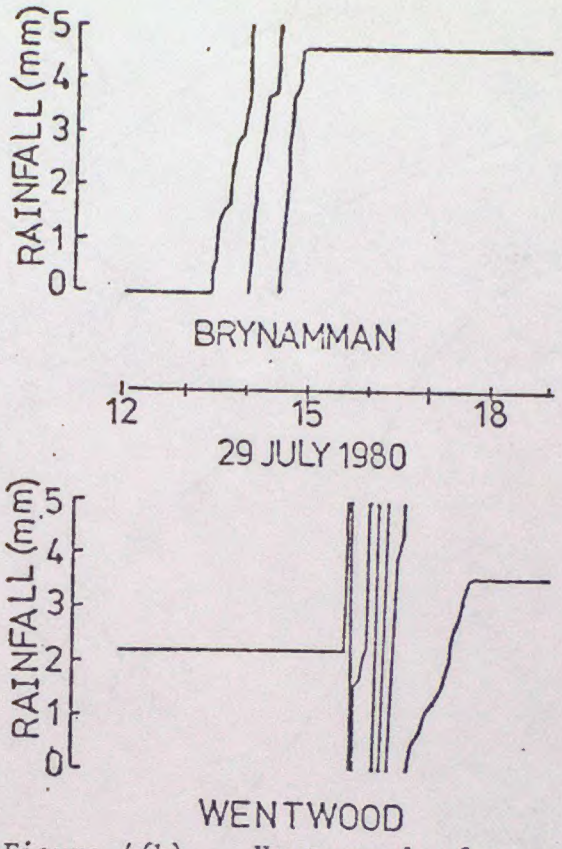

Figure 4(b). Hyetographs for Brynamman and Wentwood, south Wales (locations B and W in figure 2) showing the persistence and intensity of the rainfall.

Midlands and north of England. By late morning thunderstorms had developed bringing heavy rain and flooding to the Manchester, Burnley area but leaving the Lancashire coastal plain relatively dry. The surface observations failed to resolve this thundery activity. The radar data indicated not only the first development of showers to the south of Manchester, but also their rapid growth. The changes over 15 minute intervals as shown by radar, can be seen in figures 5(a), (b), (c). The motion of the cells, identified from tracking the radar echoes, was northward and as one intense cell then another developed and traversed the same path it was evident that large accumulations of rainfall were going to occur in the vicinity of Blackburn but that less than 50 km either side of the track of these storm conditions would be much less severe. Totals of rainfall over predefined river subcatchments derived from radar data were available in real time and

Figure 5(a)(b)(c). Radar pictures for 1145, 1200, 1215 GMT 5 June 1980. Intensity colour scheme the same as for fig 3. Rapid development of two vigorous cells near Manchester is evident. These and later cells with rainfall rates higher than 32 mm hr^{-1} moved northward crossing the Darwen subcatchment (shown by arrow) during the afternoon. No showers traversed the coastal region 25 km to the west.

5(a)

5(b)

5(c)

it can be seen from figure 6 that the Darwen subcatchment received nearly 60 mm in less than 2 hours. The temporarily obstructed drainage system in

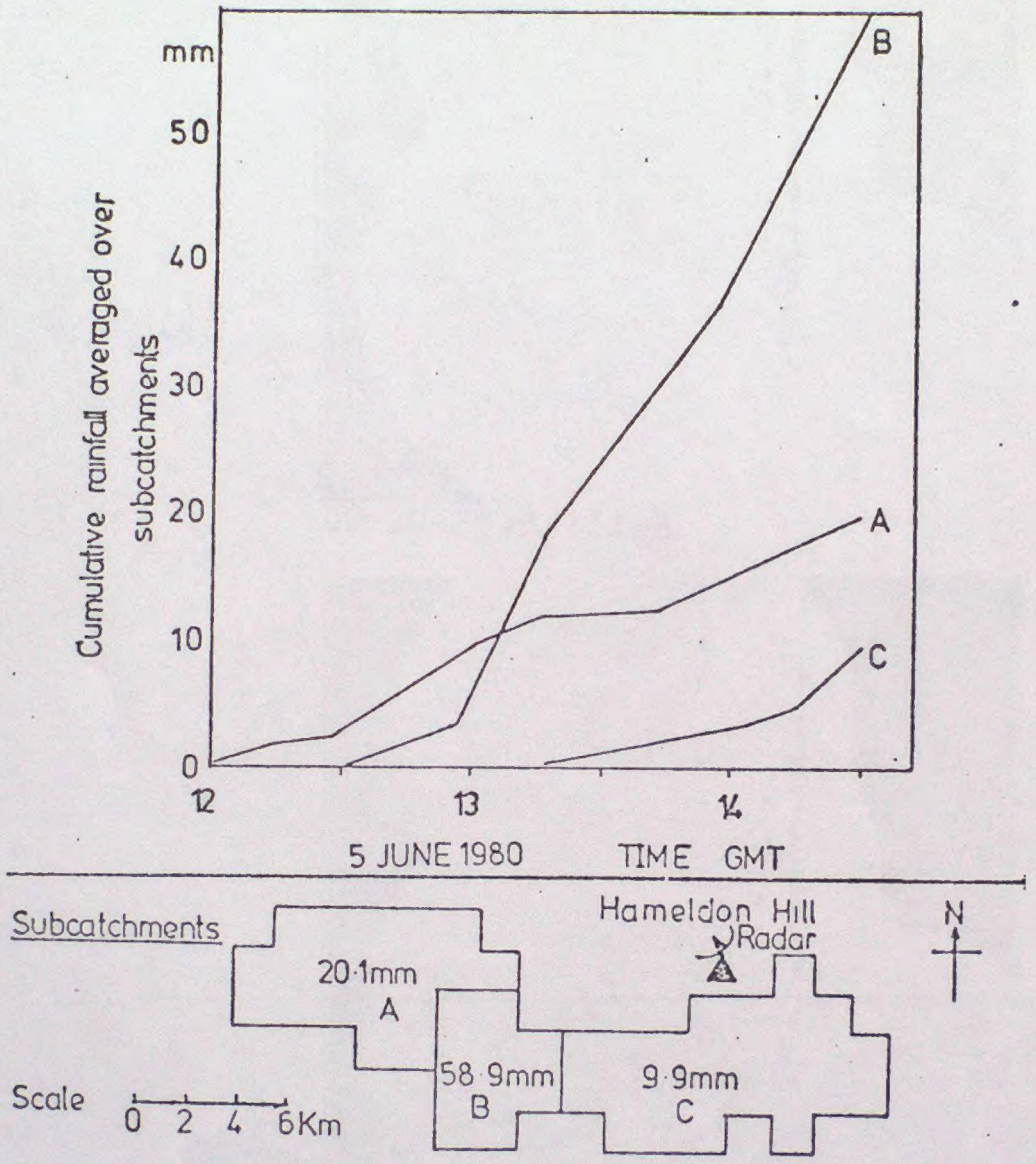

Figure 6. Variation of rainfall accumulations averaged over subcatchments derived from radar data. Figure 6(a) shows the cumulative rainfall averaged over the Darwen subcatchment (B) compared with two adjoining subcatchments (A and C). Figure 6(b) shows the location of the subcatchments and of the Hameldon Hill radar.

Darwen was unable to cope and there was extensive flooding in the town. In this particular case, the organisation necessary to take advantage of advance flood warnings may well not exist, but, through close monitoring of the radar data, up to an hours warning could have been given.

(iii) 27 December 1979

Finally, we present an example of cold frontal line convection as defined by Browning and Harrold.[7] Strong southerly winds brought moist air across the south west of England, while to the west there was a drier, northerly flow. Between these two airstreams developed line convection which was not evident from surface charts until its slow eastward motion brought it to Cornwall during the afternoon. Passage of the front brought 5 mm of rain in about 10 minutes and a marked and sudden veer and decrease

in the wind. Radar data (figure 7) showed a narrow straight line of heavy rainfall embedded within a larger area of more uniform rain. The

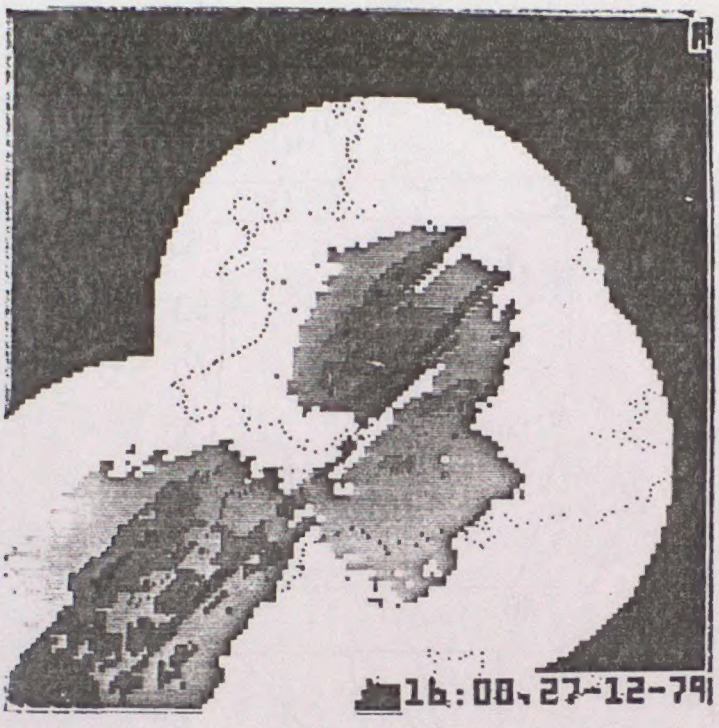

Figure 7. Radar picture for 1600 GMT 27 December 1979 showing a straight narrow band of heavy rain identified as line convection. This pattern could be recognised as early as 0900 GMT when still to the west of Cornwall and persisted for some 15 hours. Intensity colour scheme the same as for figure 3.

similarity between the anemograph traces at St Mawgan and Plymouth (figure 8) suggests that in cases of line convection it is possible to predict not only the location of significant rainfall but also the characteristics of the change in wind velocity. This has obvious application to both aviation and shipping. The line convection persisted for at least 15 hours moving slowly and uniformly eastward enabling accurate forecasts to be made up to 6 hours in advance.

(iv) Summary

Radar had three advantages over conventional observation methods in the above examples. It provided cover, with a high resolution, in areas where there was no other information; it was available at high frequency, thus showing the development of rain systems; and it was available quickly, thus, potentially, allowing some action to be taken. Radar cannot replace conventional methods, because the meteorologist depends on surface and upper air observations to calibrate and interpret the radar pictures, but it can provide a detailed picture of events as they develop.

We have presented these three cases because they are good examples of our experience that there are situations in which there is no substitute for radar data. In each case, the precise measurement of the rainfall was less important than the qualitative information that an experienced meteorologist could glean from the display. In the remainder of this paper we will address the more limited question of the use of radar data for

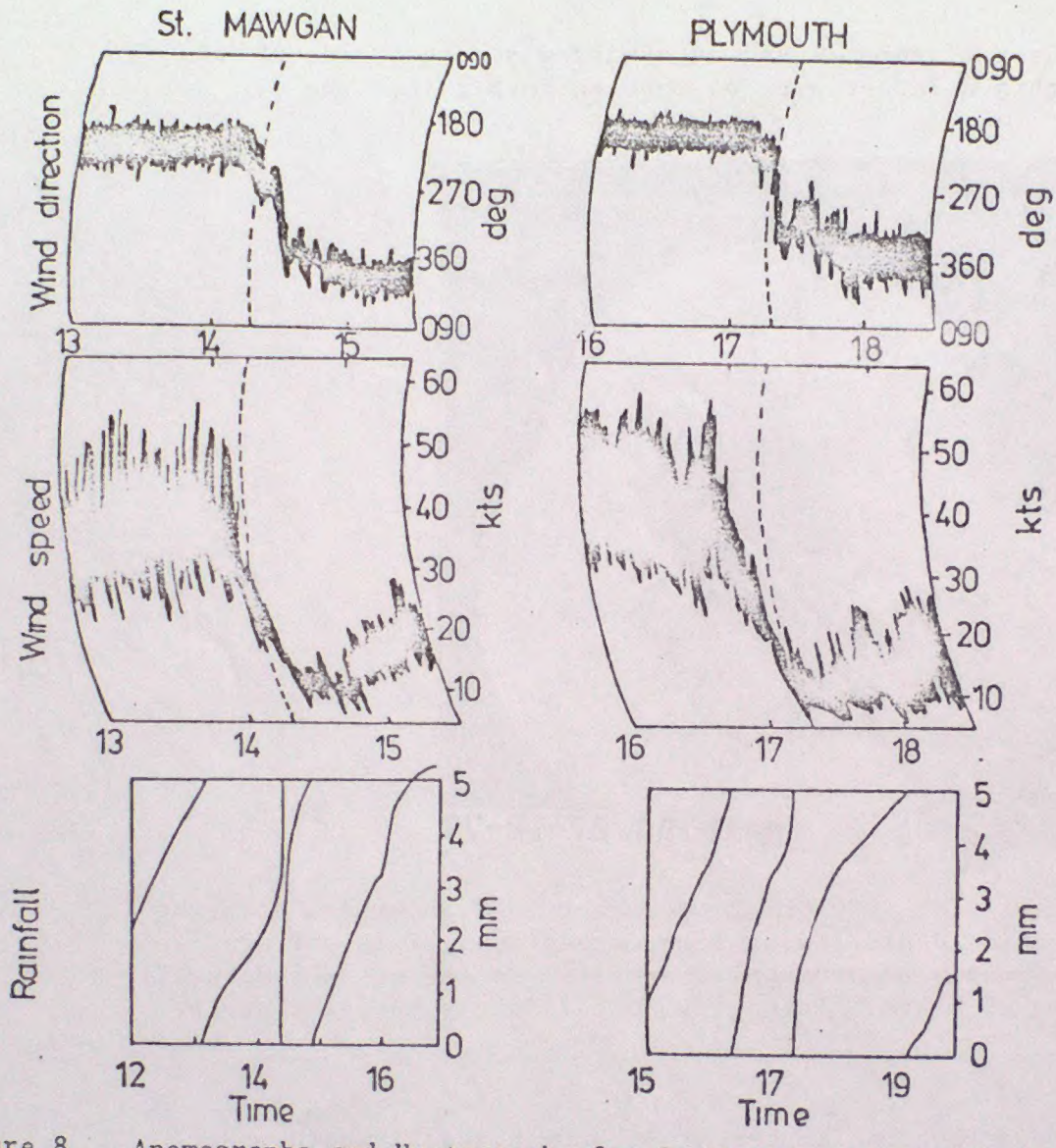

Figure 8. Anemographs and Hyetographs for St Mawgan, Cornwall and Plymouth, Devon (locations S and P in figure 2) for 27 December 1979. The dashed line corresponds to the time of heaviest rainfall at each station. Note the similarity between the anemograph traces and the sudden burst of heavy rain at the passage through each station of the line convection.

3. An Objective Forecast Model

(i) Perspective

The development of forecasting techniques using radar data has continued throughout the 1960s and 1970s, and has been reviewed by Collier.[8] Table 1 gives a summary of main types of procedure that have been described in the literature over the last ten years, together with estimates of their relative performance and speed of operation. Generally, two main types of technique have been identified:-

(i) Cross-correlation methods - Portions of one radar picture are correlated with portions of a subsequent radar picture using different picture relative displacements. When the maximum correlation is obtained the corresponding picture displacement is assumed to give the motion of the radar echoes, and is used to make forecasts.

(ii) Individual radar echo tracking methods - Individual radar echoes are identified and labelled for each radar picture. Echoes in one picture are then matched, using echo centroids or some other characteristic, with echoes in a subsequent picture in order to derive motion vectors, which are then used to produce forecasts.

Table 1 Objective forecasting using single site radar data, 1970-80

Year	Echo tracking method	Principal references	Computer requirements related to PDP-11 series computers		Accuracy, average Critical Success Index (1 hour ahead) [100 = perfect]
			Core (16 bit words)	CPU time (minutes)	
1970	Echo centroid	Barclay and Wilk	~ 24K	0.5-2.2	29
1972 1974	Weighted echo centroids	Duda and Blackmer; Ostlund	> 32K	2-10	33
1974	Cross-correlation (entire PPI)	Austin and Bellon	~ 16K	0.3	41
1976	(i) Echo edges by harmonic analysis	Muench	~ 24K	0.8	40
	(ii) Weighted echo centroids	Wiggert et al	> 32K	2-10	30
1977	Echo centroids	Wolf et al	~ 24K	0.5	30
1979	3-D echo centroids	Crane	> 32K	2-4	(40)

The cross-correlation technique is generally the simplest and most reliable when all the echoes in a radar picture move together, and if there are no significant size, shape or intensity changes from one picture to the next. However, cases of developing convective cells, orographic rainfall and differential motion within widespread rain, are not suited to this technique unless radar pictures are sub-divided into smaller areas. For these types of rainfall, which are very common in the British Isles, the cross-correlation technique approaches the individual echo tracking methods in terms of accuracy and complexity. Indeed, no one technique appears to stand out from the others as being reliable and accurate under all circumstances. The procedure that we describe below is designed to bring together the best features of the cross-correlation and individual echo-tracking techniques, but still produce rainfall forecasts within a few minutes of receiving the latest observations.

(ii) The Objective Model

The forecast, or extrapolation, procedure accepts two analyses of rainfall, separated by 15 mins, for an area of 128 x 128 5 km squares. The present network of only four radars does not provide complete coverage for

this area and there are many defects in the data. At present we make no attempt to correct the analyses eg by filling gaps between radars or correcting for bright band effects. The limitations of the data, and the steps that we are taking to remove them, have been discussed extensively elsewhere (eg Browning et al, Collier).[2,6] A detailed description of the extrapolation procedure itself is given by Collier and Larke.[1] The steps in the procedure may be summarised as follows.

Step 1 Reduce the radar network data from a 128 x 128, 5 km grid to a 32 x 32, 20 km grid. This simplifies the data base and removes scales of motion that are too small to be predictable for an hour or more ahead (eg Wilson).[9]

Step 2 Identify and label grid squares containing echoes with intensities above an input threshold value (usually 1/8 mm h^{-1}). Echo areas are defined using a single-linkage cluster technique. This is a simple form of hierarchical clustering (eg Anderberg).[10] It groups together those grid squares with echoes of intensity greater than the threshold value which lie within two grid squares in both the west-east and north-south directions. (For the areas of frontal rain dealt with in this study, this procedure led to just one cluster being identified for as much as 63% of the time; two clusters were identified for 34% of the time and three or more for 3% of the time).

Step 3 Calculate the centroid positions of all clusters without regard to echo intensity. The intensities are ignored so that anomalously intense echoes do not distort the calculations. The positions are calculated to within a fraction of an individual grid square.

Step 4 Repeat steps 1-3 for the radar network picture 15 minutes later. (We have found that the use of pairs of pictures separated by a greater time interval leads to a deterioration in the forecasts).

Step 5 Derive vectors for each echo cluster by matching centroid position for a pair of pictures, subject to the criterion that no centroid shall move further than 30 km in 15 minutes.

Step 6 Compare individual vectors with a 1 - hour running mean vector averaged over the entire area. If the individual vectors lie within a specified tolerance (6 km in 15 min) then they are accepted. Those vectors which lie outside this tolerance are rejected in favour of the running mean vector. Echo clusters smaller than a specified minimum area (3200 km^2 in the present study) are also allocated the mean vector. All vectors, regardless of whether or not they lie inside the tolerance, are used in the calculation of the running mean vector provided the clusters with which they are associated are greater than the specified minimum size.

Step 7 Derive rainfall forecasts for intervals up to 6 hours ahead of the time of the latest picture by using the vectors allocated to the echo clusters to extrapolate the full intensity pattern as defined on the 32 x 32 grid. If the locations of individual clusters forecast using this procedure are found to overlap, then an average of the intensity values in the region of overlap is taken.

Step 8 (optional) Subjectively assess the validity of the forecasts and repeat Step 7 with some or all of the objectively-determined vectors changed manually from the computer teletype.

There are several adjustable parameters inherent in this procedure and their best values will depend on the application and the type of situation studied. For example, the degradation of the data to 20 km squares and the use of a 15 min gap between analyses were chosen because they are suitable for frontal situations, which are the most common in the UK and provide the basis for most of the results presented in this paper. Collier and Larke discuss all these adjustable parameters and the reasons for the choices that are usually made.[1]

(iii) Model Performance

The objective model described above was used to forecast rainfall in 29 frontal events collected and described by Browning et al.[2] In each case, the forecast was made from a time when the rainfall was centred in the western half of the area of radar coverage so that the forecast rain did not move out of the area of radar coverage too quickly. The success of the model in these cases has been measured using the Critical Success Index (CSI), which avoids giving credit to trivial correct forecasts of no rain.

$$CSI = \frac{A}{A + B}$$

where A is the number of points for which rain is correctly forecast and B is the number of points for which the forecast was wrong. Figure 9 shows the average CSI for the 29 forecasts as a function of lead time. The three

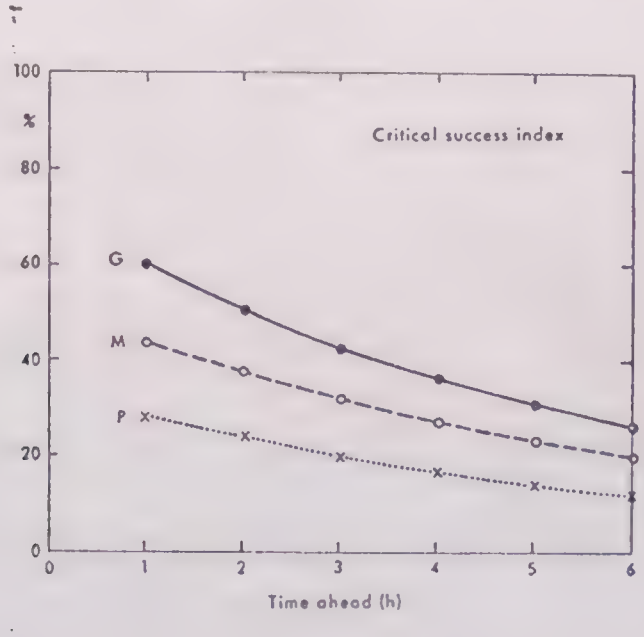

Figure 9. Critical Success Index with respect to the distribution of rain/no rain, plotted as a function of forecast lead time and averaged over all objective rainfall forecasts made during the 29 frontal events. The three curves are for areas of good (G), moderate (M) and poor (P) radar coverage, the boundaries of which are given by the 1500 m and 3000 m contours in figure 1.

curves G, M and P respectively, show the index evaluated for forecast rainfall within the areas of good, moderate and poor radar coverage defined in terms of the altitude of the radar beam - see figure 1. As is to be expected, the forecast performance shows a marked deterioration with increasing lead time. The large difference in the quality of the forecasts for the three curves is mainly due to the effect of measurement errors at long ranges on the data used as input to the forecasts. All the curves - even M and G - suffer from the fact that the forecasts are based on some initial data within the area of poor radar coverage. The especially poor performance indicated by the P curve is also due in large part to errors in the validating radar data.

In order to assess the improvement in the objective forecasts that can be achieved by manually adjusting the displacement vectors (Step 8), the Critical Success Index for the area of good radar coverage has been evaluated for forecasts made with and without this step. The vectors used in the modified analysis were chosen with hindsight so as to achieve the maximum possible improvement. The resulting curves, averaged over all the rainfall events, are plotted in figure 10. Notice the small but consistent improvement of the modified forecasts, (mod), over the unmodified forecasts, (unmod), for almost all forecast lead times. The improvement which could be

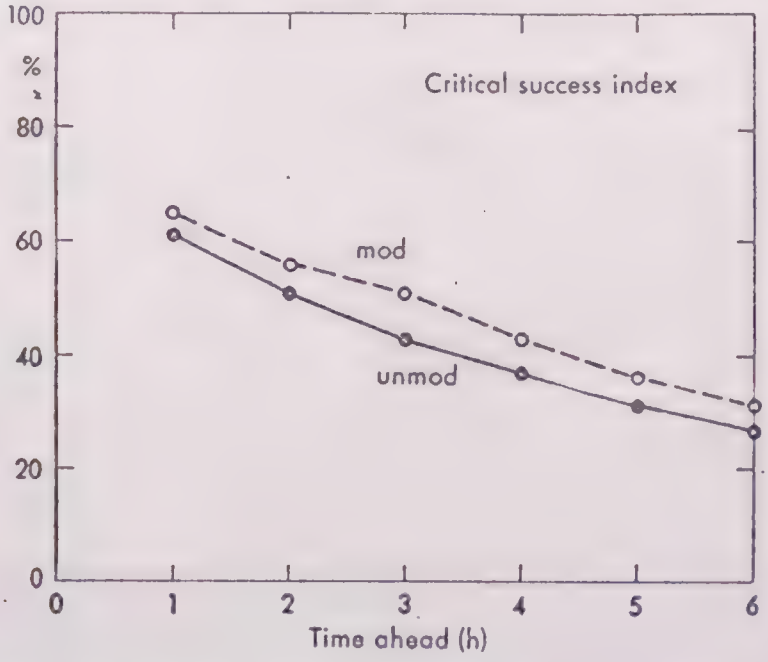

Figure 10. Critical Success Index as a function of forecast lead time averaged over all objective forecasts made during the 29 frontal events. The solid curve is for objective forecasts without any manual modification; the dashed curve is for forecasts with the displacement vectors modified subjectively.

achieved by subjectively modifying the forecasts in a real-time forecasting situation would be less than that indicated by the above curves. In practice, we suspect that, although the improvement achievable would often be rather small, it would be large in a few individual cases.

It is natural to compare the CSI of our method (65 for the modified 1 hour forecasts) with those shown in Table 1, but a number of factors limit the usefulness of this comparison. In most cases, the CSI shown in the table are depressed for at least three reasons:

(1) They have been obtained in convective situations, for which the rain cells are less persistent than for the frontal situations used by us.

(2) They have been obtained using single radars. (This should have little effect on one hour forecasts, but we include it here because it is an important limiting factor on longer time scales).

(3) The verification areas are usually smaller than the 400 km^2 used in our forecast procedure. Bellon and Austin obtained CSIs increasing from 40% to 90% as the verification area was increased from 36 to 900 km^2.[11]

The CSI is a measure of the success of forecasting whether or not it will rain; it does not test the accuracy of the amount of rainfall forecast. Figure 11 shows the average error (without regard to sign) in the rainfall forecast for a single 20 km square using the objective model. It also shows the average errors obtained using a subjective forecast method, which will be described in Section 4. In figure 11, the 29 situations used have been

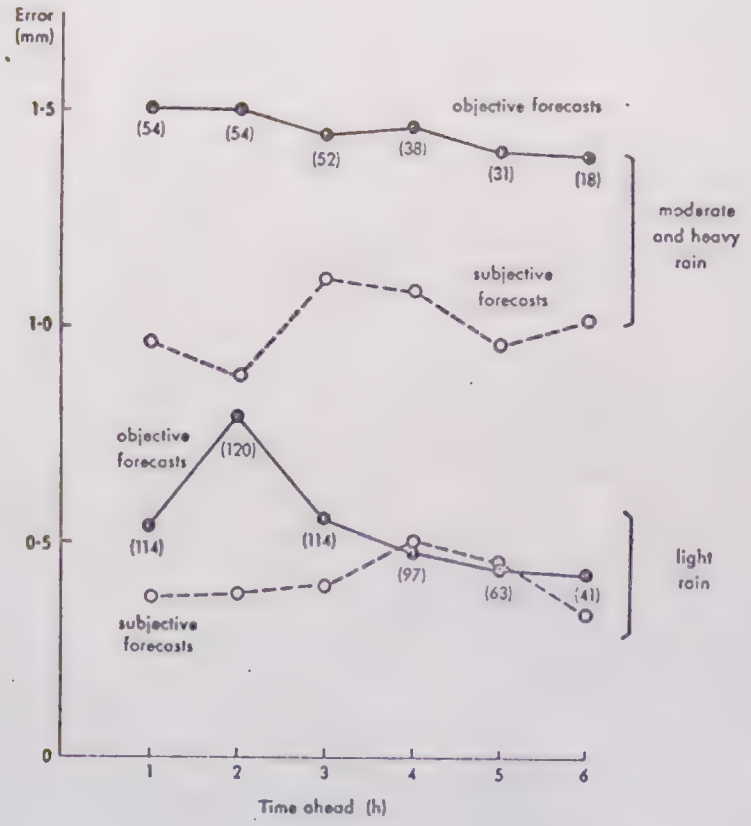

Figure 11. The mean error regardless of sign in the forecast hourly rainfall for the 20 km square centred on Malvern plotted as a function of lead time. The curves for light rain (tr - 1 mm hr^{-1}) and moderate/heavy rain (> 1 mm hr^{-1}) are shown separately. The solid curves are for objective forecasts, without manual modification, and the dashed curves are for subjective forecasts. The bracketted numbers are the number of forecasts contributing to the data point.

divided into cases of moderate or heavy rain, and cases of light rain. In the derivation of this figure the forecasts were not limited to one for each of the 29 situations, and the numbers in brackets show number of forecasts contributing to the data point. As might be expected figure 11 shows that the absolute error for the light rain cases is smaller than that for the moderate/heavy rain cases. The same tendency is also observed within the moderate/heavy category and these data have been replotted in figure 12 as a percentage error. The percentage error for the objective forecasts is seen to remain fairly constant with time at about 75%; that for the

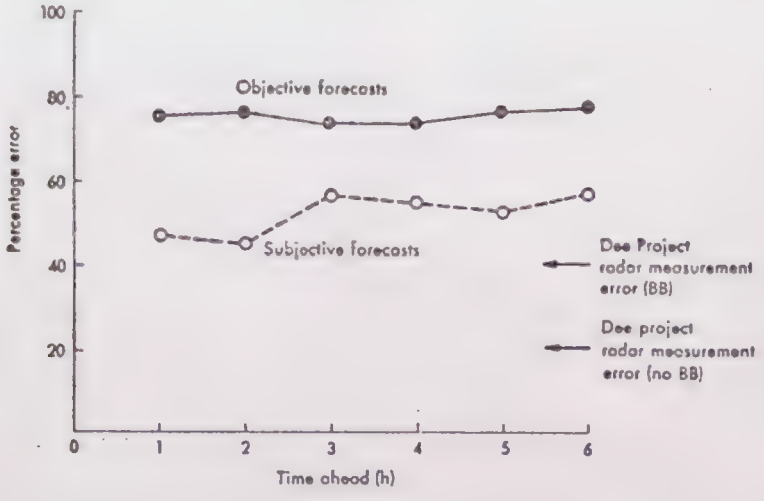

Figure 12. The average percentage error, without regard to sign, in forecasts of moderate or heavy rain. The solid line shows the results for objective forecasts, (without manual modification) and the dashed line is for the subjective forecasts. The errors in the measurement of rainfall by radar during the Dee Weather Radar Project are shown for comparison.[5]

subjective forecasts is significantly lower, a point that we shall discuss below. Some of this error is undoubtedly due to errors in the validating data, which was taken from three autographic gauges within the 20 km square target area. Nevertheless, there is plenty of scope for improving the objective forecasts. Browning et al have attributed the rather surprising constancy of the error with time to special aspects of the actual location of the verification area (Malvern), and the radars covering the areas usually upwind of Malvern.[2]

An error of 75% in the forecast rainfall might appear unacceptably large. For some purposes, such as forecasting rainfall in the catchment areas of rivers liable to flood, it certainly is very serious, and we shall show in the next section that it can be reduced significantly. However, while we should, and will, make every effort to improve the quantitative nature of our forecasts, we should not overlook the extremely useful nature of the forecasts that are already available. The error of 75% is consistent with always making the correct forecast to within a factor of 2, a variation that is modest when considered against the natural variability of rain. Rain reported as heavy will often be 8 or 16 times as heavy as rain reported as light, and practical forecasters that have access to our radar network display habitually degrade the data so that only a few rainfall rates are displayed. We expect that the public is, in practice, more concerned about whether rain will be heavy or light and of long or short duration than about the precise amount of rain that will fall. In this context, radar based rainfall forecasts that are accurate with regard to nature and timing would be a very substantial service.

(iv) Forecast in a Convective Situation

The results presented above show that the objective model has a useful level of skill in frontal situations. It is not clear that it will perform as well in convective situations. However, the model has been used, without any corrections to the cluster velocities (step 8), to give rainfall forecasts for Darwen on 5 June 1980, which is the second of the cases discussed in Section 2. Forecasts were made every 15 mins for lead times of up to 6 hours and the results are shown in figure 13.

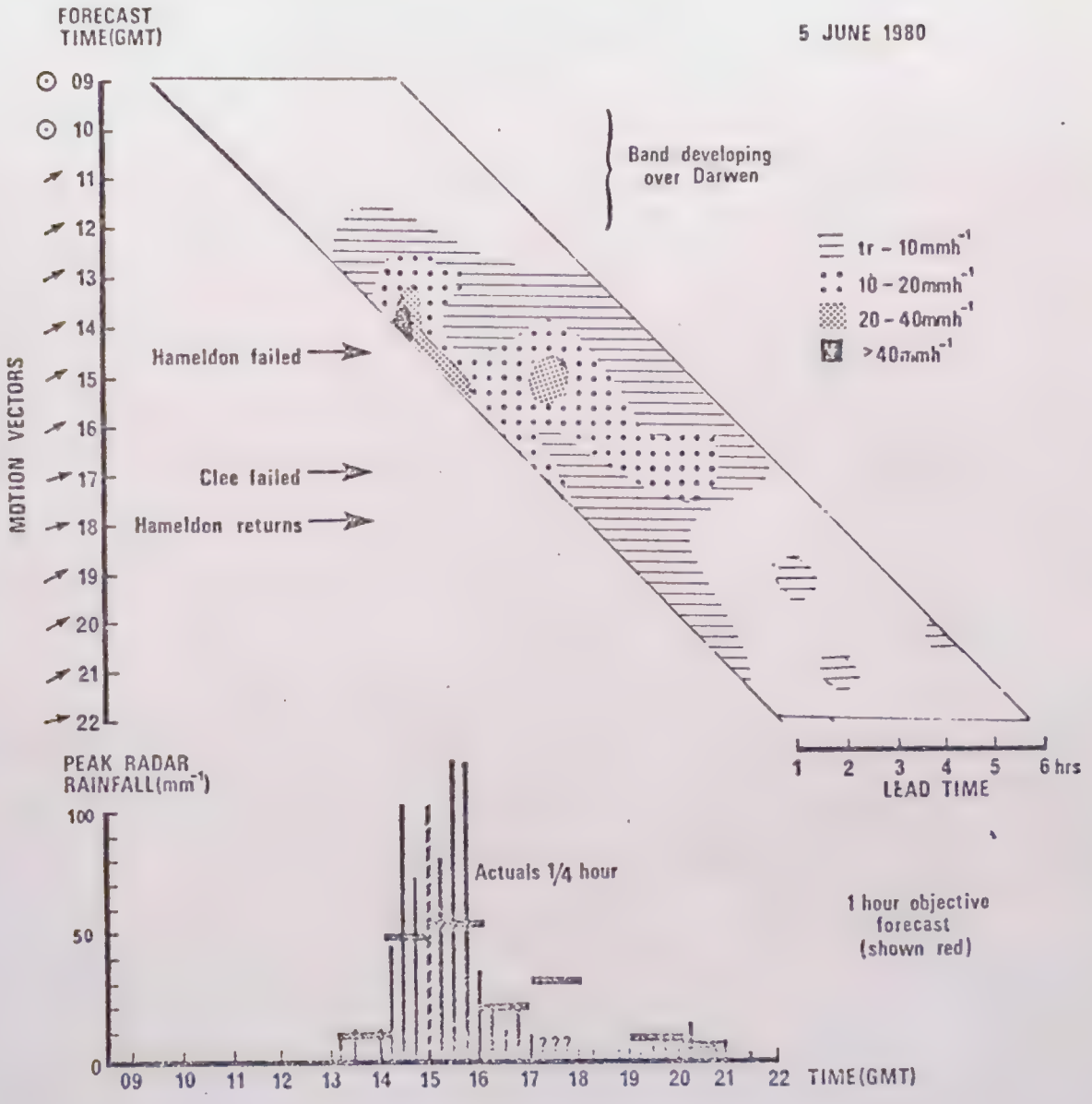

Figure 13. Forecast rainfall for Darwen on 5 June 1980 shown as a function of the initial time for the forecast and the time for which the forecast was made. In the lower part of the diagram, the one hour forecast of rain (obtained by adding four forecasts for 1/4 hour intervals) are compared, as a function of time, with the actual rainfall as observed by radar.

The upper half of figure 13 shows the forecast rainfall rate as a function of the initial time of the forecast (vertical axis) and the time for which the forecast was made (horizontal axis). If the forecasts were perfect the isopleths in this diagram would be vertical. It is clear that the fact that the convective cells developed very rapidly limited the

accuracy of the forecasts with a lead time of more than an hour. However, the forecasts one hour ahead compare very well with the actual rainfall in terms of timing and amount, as shown in the lower half of the diagram. The indications from this single case, which was chosen because of the interest of the event rather than the quality of the forecast, are that the model will be useful even in convective situations, but that we will tend to suffer a shorter lead time than in frontal situations.

(v) Summary and Future Model Development

We have shown that the model is useful and, in terms of the per: comparable with other approaches. It is readily intelligible and simple t: use and, by comparison with other procedures, very fast. Each forecast runs in about 10 secs on a PDP-11-20, and uses 20K of core.

The principal causes of forecast error will be examined in the next section. However, the results already discussed and shown in figure 10 indicate that the weakest part of the model is the calculation of the cluster velocities (defined as Type 2 errors in Section 4). This is confirmed by Collier and Larke, who have repeated rainfall forecasts for eight events using the observed 700 mb winds in place of the calculated cluster velocities, and obtained a substantial reduction (estimated by us using their graph to be 9 km ie 35%) in the spatial error of 1 hr forecasts.[1] It would certainly be possible to improve the accuracy of this calculation by using any of several complex algorithms eg finding the cluster displacement that maximises the cross-correlation between the observations of the cluster at 15 min intervals. However, that would make the model much slower, so we have preferred to include Step 8, which allows the manual correction of the cluster velocities.

In the future, rapid response interactive display systems, such as that proposed for the FRONTIERS project and described by Saker, will enable humans to replay sequences of rainfall analyses and calculate the moti- clusters by varying analogue controls until the "best fit", judged subject ively, is obtained.[12] This should be fast and reliable, and, because the judgement is made on the basis of a sequence of radar pictures, the human will automatically ignore short term variations and concentrate on the motion that persists and can therefore be extrapolated.

4. Reduction of Forecast Error

(i) A Subjective Forecasting Experiment

Browning et al have studied the sources of error in forecasts of rain using a network of weather radars.[2] A small team of forecasters monitored the network display and made forecasts of rainfall at Malvern in real time. The period of their study, November 1979 to June 1980 inclusive, was long enough to encompass a representative set of weather types over the UK. The network data were acquired and automatically archived 24 hours per day, 7 days per week. However, since the data were to be analysed by forecasters in real time, the analysis was restricted to those cases occurring during normal working hours, when precipitation was observed by radar over or upwind of certain target areas including Malvern. Despite these restrictions, a large sample of data was used in this forecasting study, amounting to approximately 400 hours of radar rainfall maps during a total of 40 events. Every effort was made in this experiment to study all kinds of rainfall situations, so considerable experience in the use of radar in non-frontal situations was acquired. However, the majority of the events were associated with frontal systems, and the detailed study of the forecasts after the event was restricted to these 29 cases.

The objective forecast procedure described in Section 3 was not

available for real time use when the experiment was carried out, so it was used later, off line, and some of the results of this work were presented in Section 3. The real time forecasts were prepared subjectively. The experience accumulated in this way enabled the forecasters to identify the various sources of error and assess their frequency of occurrence and impact on the forecast product. Although the objective forecasting procedures described in Section 3 were subjected to sensitivity tests, it would have been easy to have been misled by the rather arid statistics generated by those procedures if it had not been for the appreciation of the physical factors responsible for various errors which the forecasters were able to acquire through the subjective forecasting procedures.

Unlike the objective forecasting method, which produced detailed forecasts over large areas, the subjective forecasts were limited to a single target - specifically the 20 km square centred on Malvern - because of the sheer amount of labour involved in manually deriving frequently updated and detailed forecasts for many targets.

The basic tool used in subjective forecasting for individual targets was the x-t diagram, where x is direction 'upwind' of the target and t is time. The upwind direction is defined with respect to the movement of mesoscale precipitation areas. The x-axis need not be straight since the direction of travel of individual rain areas may vary as different parts of a synoptic-scale system approach the target zone. Neither is the x-direction always easy to locate. Rain often appears as mesoscale bands with areas of heavy precipitation within them having a component parallel to the bands. If it is not possible to resolve the motion of individual rain areas the x-direction can be taken normal to the bands. As a rain area enters the radar area, a first guess at its motion may be obtained from the 700 mb winds. When cloud imagery from a geostationary satellite is available this will provide a better indication of the motion of rain-bearing clouds approaching the radar area.

The procedure for deriving an x-t diagram is to estimate the average rainfall intensity every 1/4 h in a set of boxes upwind of the target; these are 20 km squares at close range but widen at long range to allow for directional errors (figure 14(a)). After the forecaster has plotted the rainfall values on an x-t diagram he makes a forecast by extrapolating an hours worth of data (figure 14(b)). In so doing, as discussed later, he makes subjective allowances for various sources of error in the radar rainfall data. The resulting forecasts are updated hourly (figure 14(c)) and are subsequently compared with the actual rainfall in the target square as measured using three autographic rainguages. The forecast period extends from the time at which the forecast is made to that at which a hypothetical rain cell at extreme range of radar cover would reach the target. This enables forecasts of 'no rain' to be included in a similar manner to forecasts of rain.

The average errors of these subjective forecasts is shown, as a function of lead time, in figures 11 and 12. It is quite clear that the subjective method is distinctly superior to the objective model in terms of accuracy, but we regard this as an encouraging sign. There is no difference in principle between the bases of the objective model and the subjective method just described and it is natural to infer that most of the improvement has been achieved by removing gross errors from the initial rainfall fields. It should be possible to extract the lesson learnt from these laborious subjective forecasts and apply it in an operationally feasible framework.

(ii) Sources of Forecast Error

The concept of deriving forecasts from the extrapolation of rainfall patterns observed at frequent intervals is very simple. However its

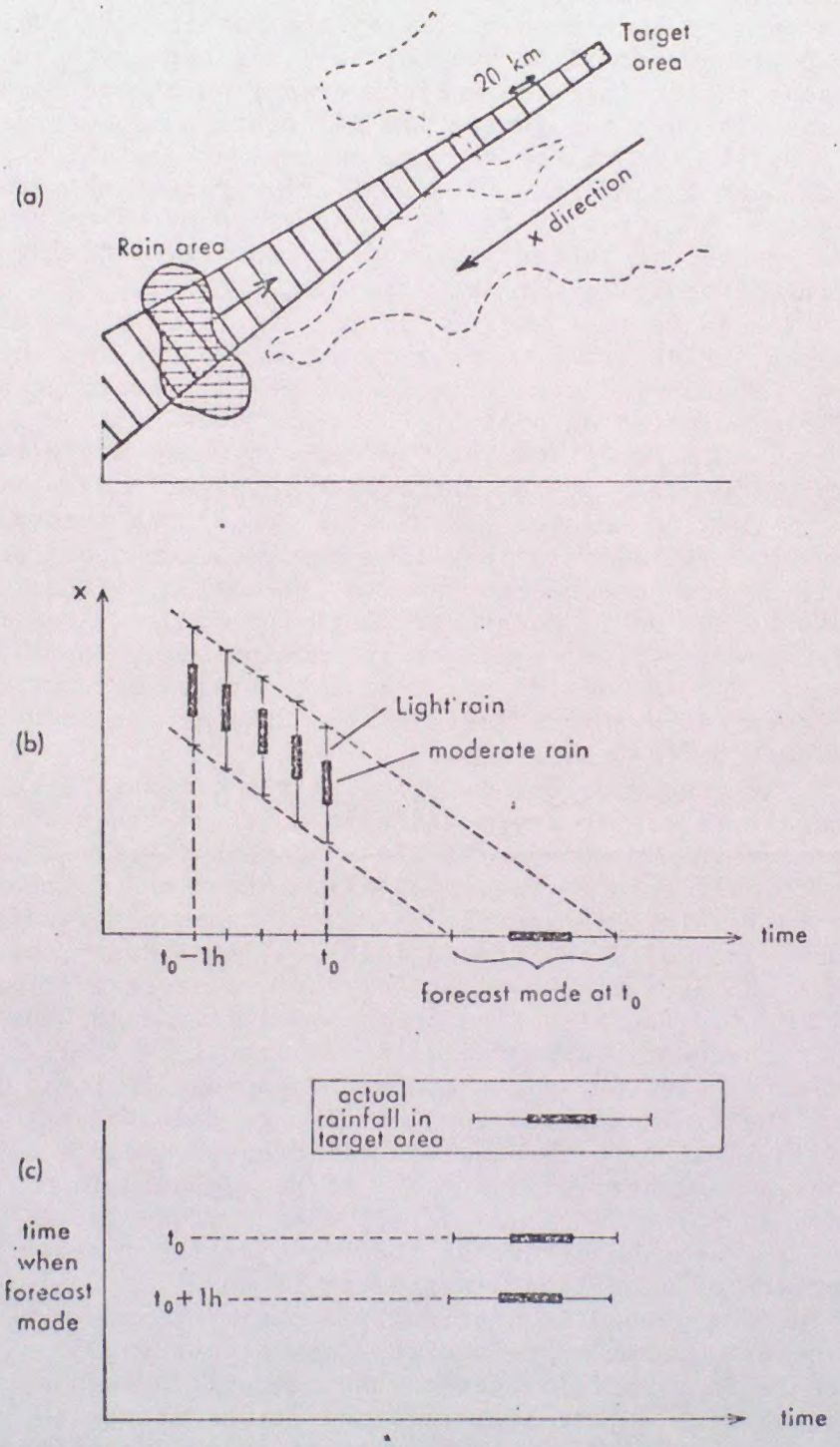

Figure 14. Schematic depiction of the x-t procedure used for subjectively forecasting the rainfall for individual target areas. See text for details.

application is complicated by several sources of error. These have been divided into four main categories by Browning et al:[2]

Type 1: Errors in estimating the actual spatial distribution of surface rainfall rate from radar data. Known sources of error include variations in the appropriate radar calibration (eg Larke and Collier), the radar beam overshooting precipitation at long range, the low level growth of rain due to orographic enhancement (Hill and Browning), the low level evaporation of rain, the bright band intensification of the radar echo from melting snow and echoes from the ground due to the variable or anomalous propagation of the radar beam.[13,14]

Type 2: Errors in estimating the actual velocity of the rainfall pattern. This applies particularly in the case of the objective model, but forecasters will also make mistakes, often because of Type 1 errors or the limited range of the radar.

Type 3: Errors due to temporal changes in the intensity of the rainfall pattern.

Type 4: Errors due to temporal changes in the velocity of the rainfall pattern.

Type 1 and 2 errors limit our ability to understand the current rainfall distribution and therefore our ability to forecast future rainfall. Type 3 and 4 errors limit the validity of the method we have chosen ie linear extrapolation of the observed rainfall patterns.

The principal sources of error in each subjective forecast were identified as part of the forecasting procedure. The results are shown in Table 2. The effect of these errors on the accuracy of forecast hourly rainfall totals has been evaluated in terms of the number of rainfall events affected (n) and their mean error ($\bar{\varepsilon}$, averaged for each event over cell forecasts with lead times from 1 to 6 hours). The overall importance of each error is measured by the summation $\sum^{n} \bar{\varepsilon}$ (rounded to the nearest 5 mm). The values in brackets are the actual errors derived in real time when some correction was made, where possible, to minimise the effects of the errors, and the unbracketted values are the errors that would have been incurred in the absence of any such corrections.

We can see that 50% of the inaccuracy of rainfall forecasts obtained by extrapolating radar data are probably attributable to Type 1 errors ie difficulty in inferring the actual surface rainfall. Type 2, 3 and 4 errors account for about 15%, 20% and 5% of the inaccuracy. This was the first experience in the UK Met Office of real time monitoring and use of a radar network display, and yet subjective intervention improved the accuracy of the forecasts by about 25%. Again, we are encouraged by the facts that most of the errors are in the interpretation of the radar display rather than the extrapolation and that they appeared to be amenable to subjective intervention. We conclude that, at this stage, the greatest benefit will be obtained by improving the interpretation of the radar data in terms of surface rainfall. To this end, Browning has proposed the FRONTIERS plan for optimising rainfall analyses based on radar, and satellite, data by using an interactive visual display system of the sort described by Saker.[15,12]

5. Conclusion

The most immediate impact of radar data in a forecasting environment is on the meteorologist's understanding of the general situation. We have presented three cases where a complete understanding of events was only

Table 2 Principal sources of error in the subjective rainfall forecasts for Malvern during 29 frontal rainfall events

Source of error	Type (see Sec 3)	Number of rainfall events affected (n)	Measure of importance* of the errors bef... (after) making subjective corrections.
Development or decay of rain areas	3	16	20 (20)
Beam overshooting shallow precipitation	1	14	20 (10)
Difficulty in defining motion due to amorphous structures of rain areas	2	9	15 (10)
Radar calibration changes** and dropsize variability	1	10	10 (10)
Low-level evaporation	1	14	10 (5)
Bright band	1	8	10 (5)
Changes in velocity of rain areas	4	5	5 (5)

* See text for explanation of units
** Discounting known long-term errors

possible through the use of radar data. There are many other cases that we have not shown where a display of merged data from a network of radars would confirm and clarify the situation, or even provide a fresh interpretation, and thus enable the forecaster to advise the public with confidence. This potential will only be released by extending the availability of network radar data, and making every effort to improve its conversion into rainfall analyses.

In whatever terms it is subjectively understood, radar actually observes rain and it is natural that most of our work has been on the problem of forecasting rain. We have pointed out that one should not become obsessed with the goal of quantitative accuracy to the exclusion of a more qualitative but very valuable product. The most important requirement is for forecasts of "when", "for how long" and "where" it will rain, and advice as to whether the rain will be "very heavy", "heavy" or "light". There is every reason to suppose that our objective model, based on rainfall analyses obtained using the FRONTIERS interactive display, will meet this requirement for forecasters in the period 1 to 6 hrs ahead.

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